

**THE STRETCHED LENS ARRAY (SLA):
A LOW-RISK, COST-EFFECTIVE CONCENTRATOR ARRAY OFFERING
WING-LEVEL PERFORMANCE OF 180 W/KG AND 300 W/M² AT 300 VDC**

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ABSTRACT

At IECEC 2001, our team presented a paper on the new stretched lens array (SLA), including its evolution from the successful SCARLET array on the NASA/JPL Deep Space 1 spacecraft. Since that conference, the SLA team has made significant advances in the SLA technology, including component-level improvements, array-level optimization, space environment exposure testing, and prototype hardware fabrication and evaluation. This paper describes the evolved version of the SLA, highlighting recent improvements in the lens, solar cell, photovoltaic receiver, rigid panel structure, and complete solar array wing. In addition to excellent durability in the space environment, the near-term SLA will provide outstanding wing-level performance parameters:

- > 180 W/kg Specific Power
- > 300 W/m² Power Density
- > 300 V Operational Voltage
- > 85% Savings in Cell Area (cm²/W) and Cell-Related Cost (\$/W) Compared to Planar Arrays
- > 9 kW/m³ stowed power at launch.

The following sections of this paper provide more details on SLA and on the key advances made in SLA technology since IECEC 2001.

INTRODUCTION AND BACKGROUND

Since 1986, ENTECH and NASA have been developing and refining space photovoltaic arrays using refractive concentrator technology [1]. Unlike reflective concentrators, these refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors, enabling straightforward manufacture, assembly, and operation on orbit. By using a unique arch shape, these Fresnel lenses provide more than 100X larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators [2].

In the early 1990's, the first refractive concentrator array was developed and flown on the PASP Plus mission, which included a number of small advanced arrays (3). The refractive concentrator array used ENTECH mini-dome lenses over Boeing mechanically stacked multi-junction (MJ) cells (GaAs over GaSb). The mini-dome lenses were made by ENTECH from space-qualified

silicone (DC 93-500), and coated by Boeing and OCLI to provide protection against space ultraviolet (UV) radiation and atomic oxygen (AO). This array performed extremely well throughout the year-long mission in a high-radiation, 70-degree inclination, 363 km by 2550 km elliptical orbit, validating both the high performance and radiation hardness of the refractive concentrator approach (3). In addition, in high-voltage space plasma interaction experiments, the refractive concentrator array was able to withstand cell voltage excursions to 500 V relative to the plasma with minimal environmental interaction [3].

In the middle 1990's, ENTECH and NASA developed a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator. Using a continuous roll-to-roll process, 3M can now rapidly mass-produce the line-focus silicone lens material in any desired quantity.

In 1994, AEC-ABLE joined the refractive concentrator team and led the development of the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array [4]. SCARLET uses a small (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction cells. Launched in October 1998, a 2.5 kW SCARLET array powered both the spacecraft and the ion engine on the NASA/JPL Deep Space One probe, shown in Fig. 1. SCARLET achieved over 200 W/sq.m. areal power density and over 45 W/kg specific power [5]. With SCARLET working flawlessly, Deep Space 1 had a spectacularly successful rendezvous with the comet, Borrelly, in September 2001, capturing the highest-resolution images of a comet to date and other unprecedented comet data.

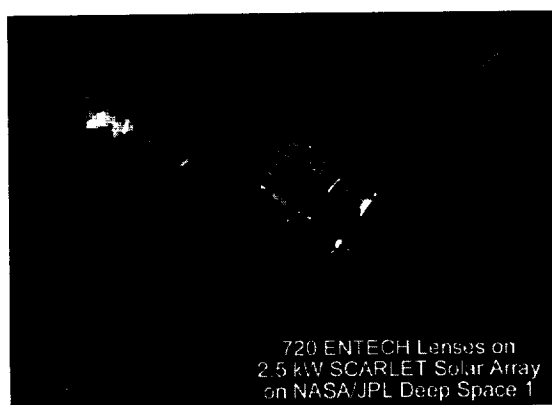


Fig. 1 – SCARLET Array on Deep Space 1

Over the past three years, the team, including Auburn's Space Research Institute, has been developing a new space concentrator array technology, called the stretched lens array (SLA). SLA provides even higher performance than SCARLET at dramatically reduced mass and cost [6 and 7]. The following paragraphs describe SLA progress in the past year since the last IECEC paper [8].

THE STRETCHED LENS

The patented SLA uses a thin, flexible, linear Fresnel lens optical concentrator to focus color-mixed sunlight onto multi-junction solar cells [9 and 10]. The lens is made by 3M using a high-speed, continuous, roll-to-roll process, from space-qualified silicone rubber material (DC 93-500). For the SCARLET array and for the original SLA, the lens material was about 275 microns thick, comprising 100 micron tall prisms on a 175 micron base. In 2001, 3M conducted a trial run of much thinner lens material, comprising the same 100 micron tall prisms on an 87 micron base. Since the prism layer is half void, the total mass of the thinner lens material is 40% less than for the thicker material. Despite this drastic reduction in thickness and mass, the new ultra-thin lens material maintained the same high optical efficiency of $92\% \pm 1\%$, when tested at 9X geometric concentration using a GaInP single-junction reference cell (Fig. 2).



Fig. 2 – Ultra-Thin Lensfilm Test

ABLE thermal-cycled a deployed thin lens sample with no mechanical failure, and NASA Marshall exposed a deployed thick lens sample to electrons with no measurable optical loss, as summarized below:

Type of Test	Exposure	Rationale
Thermal Cycling (Thin Lensfilm)	1,800 Cycles from -180C to +120C	Equivalent to 20 Years on GEO
Electrons (Thick Lensfilm)	1×10^{15} @ 1 MeV	Standard Solar Cell Test (Additional Testing Planned)

Non-prismatic samples of the silicone material used to make the lens have also been subjected to combined vacuum ultraviolet (VUV, from 119 to 200 micron wavelength) and near ultraviolet (NUV, from 200 to 400 nm wavelength) exposure testing by NASA Marshall [11].

One recent lens material sample was coated by ZC&R Optical Coatings with a multi-layer UV-rejection (UVR) coating like the coating successfully used on the silicone mini-dome lenses on the PASP Plus flight test, with very encouraging results (Fig. 3). Despite the very low wavelength output of the VUV lamp (80% of the lamp power was below 170 nm, a spectral region containing less than 0.001% of the total AM0 sunlight irradiance), the transmittance loss was relatively small after nearly 7,800 equivalent sun hours (ESH) of combined NUV/VUV exposure. Indeed, when the spectral transmittance curve is convolved with the quantum efficiency curve of the top cell (GaInP) in the triple-junction stack, the net current loss under AM0 sunlight is about 5%. With proper tailoring of the initial top-to-middle cell current ratio, the effective loss in total cell power output can be less than 2.5% due to this effect. Additional work is ongoing to better understand the UV degradation phenomena and to thereby improve the UVR coating. In addition, a flight test of coated versus uncoated lens material is badly needed to quantify the actual UV degradation effect in space, since this effect is very difficult to accurately simulate in ground testing.

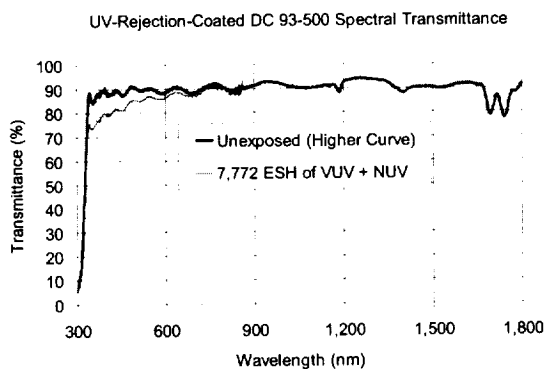


Fig. 3 – Combined VUV/NUV Exposure Results

THE SOLAR CELLS

Both Spectrolab and EMCORE have recently provided improved triple-junction (GaInP/GaAs/Ge) concentrator cells for the SLA. The Spectrolab cells are fully described in a recent paper [12]. The concentrator cells have a 1.0 cm active width between parallel busbars, corresponding to 8.5X geometric concentration ratio, since the lens has an aperture width of 8.5 cm. The 3.5-cm-long Spectrolab cells included 94 cells with parallel gridlines spaced on 254 micron centers, to be compatible with one version of ENTECH's prismatic cell cover, which eliminates the normal gridline shadowing loss. Spectrolab tested these 94 bare cells at both 1 AM0 sun irradiance and 8 AM0 suns irradiance, with the results shown in Fig. 4. As expected, the cell efficiency is significantly higher at 8 suns irradiance. The average cell performance gain due to concentration is 11% for all 94 cells. Interestingly, this gain effectively offsets the transmittance loss of the lens, boosting SLA's outstanding performance.

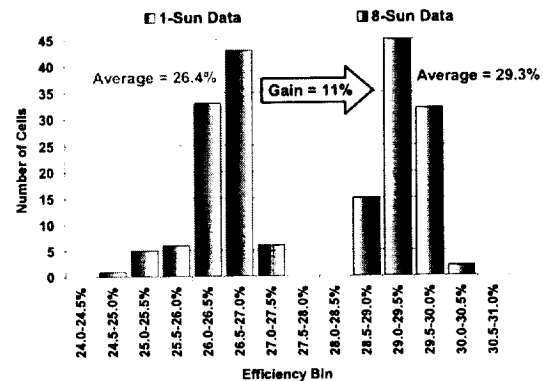


Fig. 4 – Spectrolab Bare Cell Performance

Note that the 11% relative gain in cell efficiency at 8 suns compared to 1 sun is accompanied by a tightening of the cell performance distribution. Only 4 cell efficiency bins are required to contain all 94 cells at 8 suns, compared to 6 cell efficiency bins at 1 sun. The 29.3% average bare cell efficiency is expected to increase to about 31% when prismatic cell covers are applied to these cells, considering the 6% grid shadowing factor. As discussed in the following section, Spectrolab cells equipped with prismatic covers have demonstrated outstanding performance in recent NASA Glenn testing.

The 4.0-cm-long EMCORE sample cells use a closer grid spacing (127 microns on centers), with a correspondingly higher grid shadowing loss (about 16%). Prismatic cell covers are essential to good performance for these highly metallized cells. As discussed in the following section, EMCORE cells equipped with the prismatic covers have also provided outstanding performance in recent NASA Glenn testing.

COMBINED LENS/CELL MODULES

In recent months, several combined lens/cell modules have been fabricated and flown on the NASA Glenn Lear Jet to determine their AM0 short-circuit currents. These currents have then been used to calibrate NASA Glenn's large area pulsed solar simulator (LAPSS) during full IV curve testing of the same SLA modules. SLA modules using the new ultra-thin lensfilm and prism-covered cells from both Spectrolab and EMCORE have been tested by NASA Glenn using this combined Lear/LAPSS approach, with outstanding results. Fig. 5 shows one of the SLA modules during outdoor ground testing at ENTECH, prior to delivery to NASA Glenn for Lear and LAPSS testing. The unit was sized to fit within the sun-pointing tube on the NASA Glenn Lear Jet. Fig. 6 shows the NASA-Glenn-measured AM0 IV curve for the SLA module using a prism-covered EMCORE cell. Fig. 7 shows the NASA-Glenn-measured AM0 IV curve for the SLA module using a prism-covered Spectrolab cell. Note that both modules have net electrical conversion efficiencies over 27% under AM0 sunlight at room temperature (25C). Since these SLA



Fig. 5 – SLA Module for Lear/LAPSS Testing

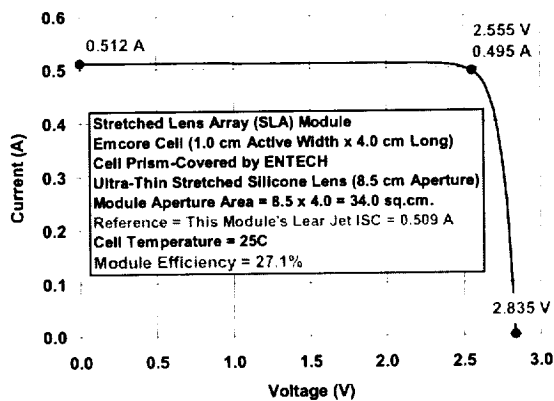


Fig. 6 – 27% SLA Module Using EMCORE Cell

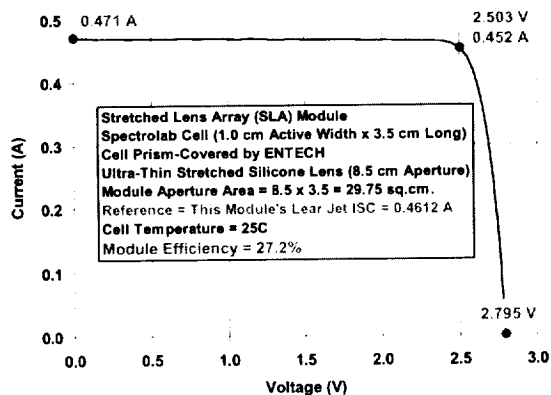


Fig. 7 – 27% SLA Module Using Spectrolab Cell

module efficiency values are based on the measured short-circuit currents from the Lear Jet flights, they also include any optical losses due to imperfect sun-pointing during the Lear Jet flight.

MICROMETEOROID HYPERVELOCITY IMPACT TESTING IN PLASMA

Auburn University's Space Power Institute has conducted numerous simulated micrometeoroid impact tests (at 10-12 km/sec) of both lens and photovoltaic receiver samples in a plasma chamber [13]. These tests included:

- Stretched Lenses Alone
- Receivers Alone
- Combined Lenses over Receivers
- Front and Back Impact
- Cells Biased at -400 V and -1,000 V (Negative) Relative to Plasma During Tests.

The lens impact tests showed clean penetrations with no peripheral damage such as tearing (Fig. 8).

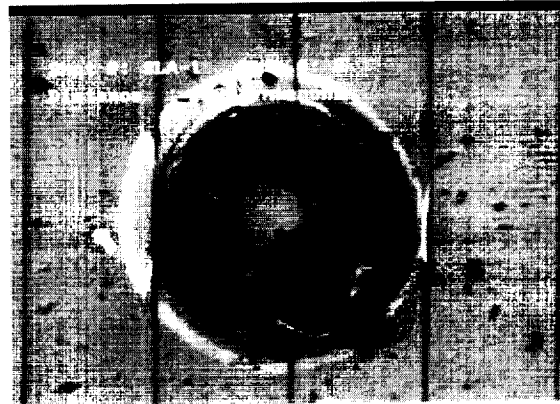


Fig. 8 – Stretched Lens Sample Showing Micrometeoroid Puncture

ENTECH mounted the single-cell photovoltaic receivers to composite radiator sheet, and fully encapsulated the receivers to enable high-voltage operation. Two of the receivers were tested multiple times (Fig. 9). Auburn first tested these receiver samples in a simulated LEO plasma, with the cells biased to more than 400 volts (negative) relative to the plasma. Micrometeoroids were then shot at the samples, causing minor damage to the cover glass over each cell, but no electrical discharge or current leakage problems were observed. After this successful test, the receiver samples were re-tested, with the cells biased to more than 1,000 volts (negative) relative to the plasma. Micrometeoroids were then shot again at the samples, and the only discharge which occurred was a transient event due to a puncture of the polyimide tape over the lead wire located inside the white circle in Fig. 9. This event was self-healing, with no lasting leakage current to the plasma. Despite many impacts over the photovoltaic receivers, as evidenced by the many pockmarks in the photo in Fig. 9, the receivers had no discharge events during or after these tests.

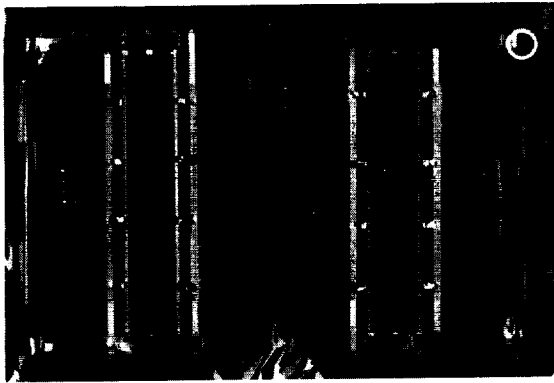


Fig. 9 – Photovoltaic Receiver Samples
After Micrometeoroid Impact

A final set of tests was conducted with the lens stretched in front of the receivers to simulate the flight-like configuration. The receivers were once again held at 1,000 V (negative) relative to the plasma. Micrometeoroids were first shot at the front (lens side) of the units, and the lens proved to be an excellent natural micrometeoroid shield for the receivers, preventing any direct impact on the receivers. Micrometeoroids were then shot from the back (radiator side) of the units. No discharge problems of any kind occurred during or after these combined lens/receiver tests.

This high-voltage capability, with very little mass penalty, is one of the key advantages of the SLA approach over conventional planar arrays. The small cells can be super-insulated without adding much mass to the array, due to the small size of the solar cells. For high-power arrays (e.g., 20 kW and larger), this high-voltage capability provides significant savings in wiring mass and cost compared to conventional lower-voltage planar arrays. The added encapsulation can also be designed to provide excellent radiation tolerance for high-radiation missions.

THE SOLAR ARRAY WING

Initially, the SLA team was considering a flexible blanket solar array wing approach for SLA [6]. This approach has now been superseded by a more conventional rigid panel wing approach, with spring-driven, self-deploying end arches to support the stretched lenses (Fig. 10). By using ultra-light, single-face-sheet, picture-frame panels for all but the innermost and outermost panels of the wing, the rigid panel wing is superior to the blanket wing in performance, mass, cost, flight heritage, and marketability. A subscale prototype four-panel wing has been fabricated and evaluated mechanically, as shown at the bottom of Fig. 10. This wing will be equipped with a full complement of lenses and several “live” solar cell strings later this year.

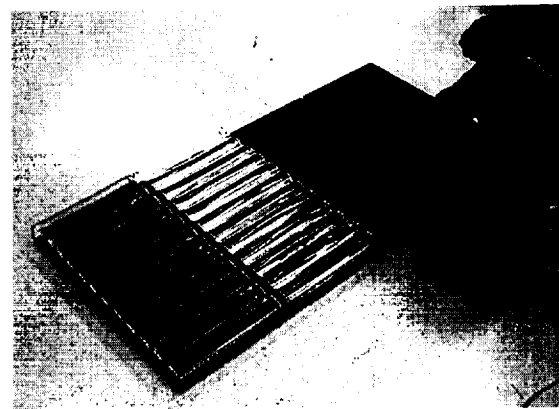
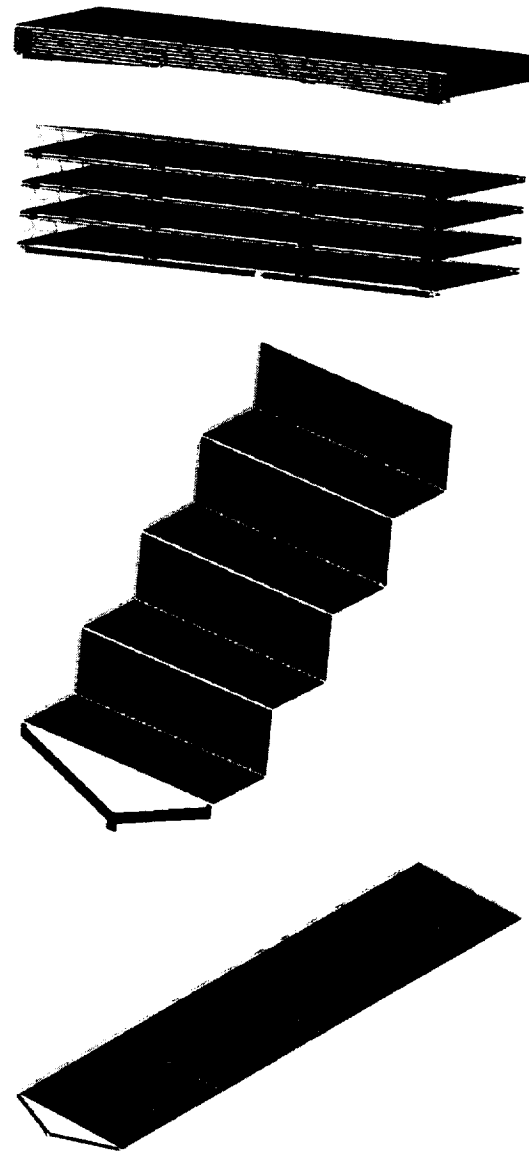


Fig. 10 – Rigid Panel SLA Wing Approach

WING-LEVEL PERFORMANCE

A detailed analysis has been conducted for a 7 kW rigid-panel SLA wing, resulting in the following full-wing performance estimates (on-orbit beginning of life, BOL):

- Areal Power Density: 300 W/sq.m.
- Specific Power: 180 W/kg
- Stowed Power Density: 9 kW/cu.m.
- Stiffness (Stowed/Deployed): 40 Hz / 0.1 Hz
- Operational Voltage: 300 V

SYNERGY WITH TERRESTRIAL PHOTOVOLTAICS

Although the multi-junction solar cells used in SLA have been optimized for the AM0 spectrum, they work exceptionally well under ground sunlight as well. Indeed, the latest lens/cell modules have been routinely tested outdoors at ENTECH with measured net operational solar-to-electric conversion efficiency values above 30%. Fig. 11 shows a typical measured IV curve for a lens/cell unit tested outdoors under terrestrial sunlight. This ambient-air-cooled mini-concentrator module measured over 30% net lens/cell module efficiency, when the direct normal solar irradiance was 851 W/sq.m. (measured by an NREL-calibrated Epopley normal incidence pyrheliometer) and the ambient air temperature was 25C. These measurements are believed to represent the first time that a solar energy device of any kind has been measured outdoors under actual sunlight at over 30% net operational solar-to-electric efficiency [14].

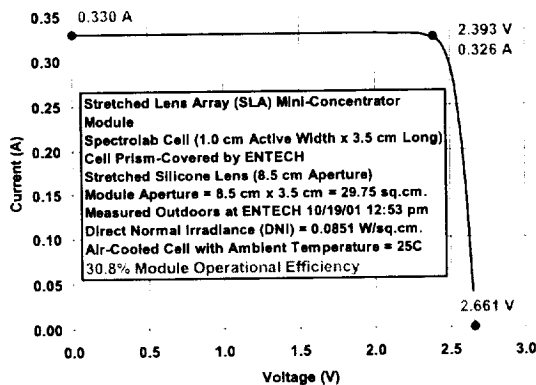


Fig. 11 – 30% Efficient Stretched Lens Module with Spectrolab Cell Tested Under Ground Sunlight

CONCLUSIONS

A new lightweight rigid-panel concentrator array is under development for future space power applications. SLA provides a substantial cost advantage over planar arrays by using only one-eighth as much expensive solar cell material for the same power output. In addition, the thin silicone lensfilm and the thin composite sheet radiator

provide a substantial mass/area advantage over conventional planar cell assemblies. The new rigid-panel SLA wing employs a conventional, conservative, well-proven approach to array deployment and support on orbit, while offering outstanding performance, high-voltage capability, and radiation tolerance. The error-tolerant SLA builds upon the proven flight heritage of the SCARLET array, and represents a low-risk, cost-effective concentrator array for future missions from LEO to deep space.

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